

Neutron Beta Decay Correlation Measurement with Pulsed Cold Neutrons

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Physics division, LANL
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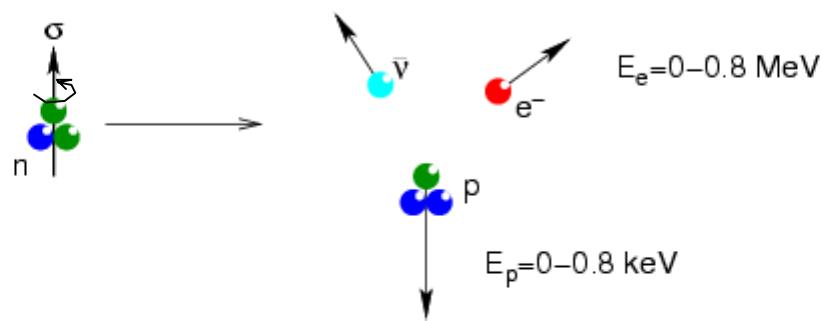
Introduction

- Standard Model is very successful describing subatomic physics
Quarks, Leptons, Gauge particles
- SM is incomplete
 - Neutrino masses
 - Unification of strong and electroweak forces
 - Gravity
 - Mixing angles
- Prediction of SM can be experimentally tested
 - High-energy searches for new particles
 - Low-energy precision measurements

The Neutron

- Simple system - udd quark composition
 - Decays by $d \rightarrow u$ weak interaction
 - Can measure neutron lifetime, decay correlation constants, energy spectra
-
- Cold neutron : moderated by LH_2 , ~meV
 - Polarized neutron (spin $\frac{1}{2}$)
 - Pulsed neutron : P_n

Neutron β -decay

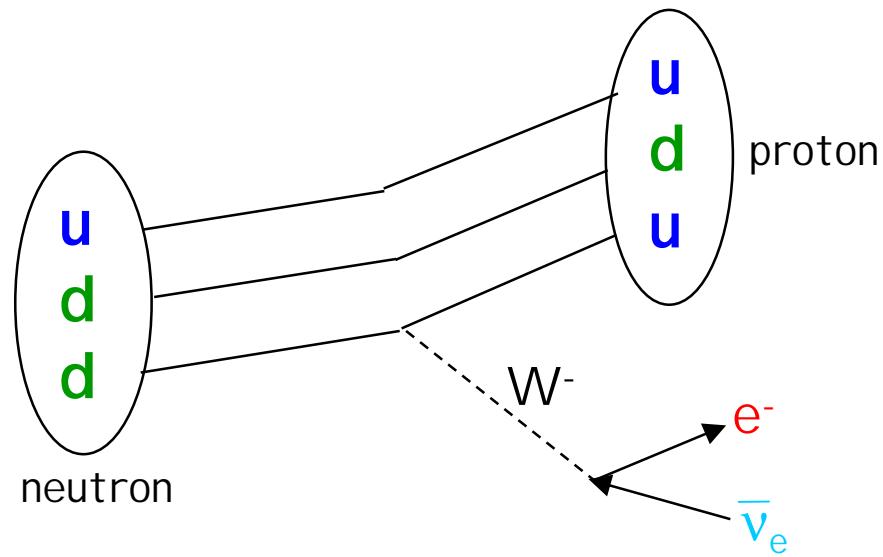


$$d\Gamma \propto p_e E_e (E_{\max} - E_e)^2 dE_e d\Omega_e d\Omega_\nu \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + P_n \left[A \frac{\vec{p}_e \cdot \vec{\sigma}}{E_e} + B \frac{\vec{p}_\nu \cdot \vec{\sigma}}{E_\nu} \right] + b \frac{m_e}{E_e} \right]$$

↑
Neutron polarization

Correlation: a, A, B, b

Neutron β -decay in quark picture



In SM,

- $d \rightarrow ue^-\bar{\nu}_e$ comes from W exchange in weak interaction.
- a , A , and B depend on two coupling constants, G_A and G_V .

In SM of V-A weak interaction

Determine λ

$$\left\{ \begin{array}{l} a = \frac{1 - \lambda^2}{1 + 3\lambda^2}, \quad b = 0, \\ A = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2}, \quad B = 2 \frac{\lambda^2 - \lambda}{1 + 3\lambda^2} \end{array} \right.$$

Determine G_V

$$\tau_n = \frac{\text{constant}}{G_V^2 (1 + 3\lambda^2)}$$

τ_n is known to 0.2% $\rightarrow 0.02\%$

Determine G_A

$$\lambda = \frac{G_A}{G_V}$$

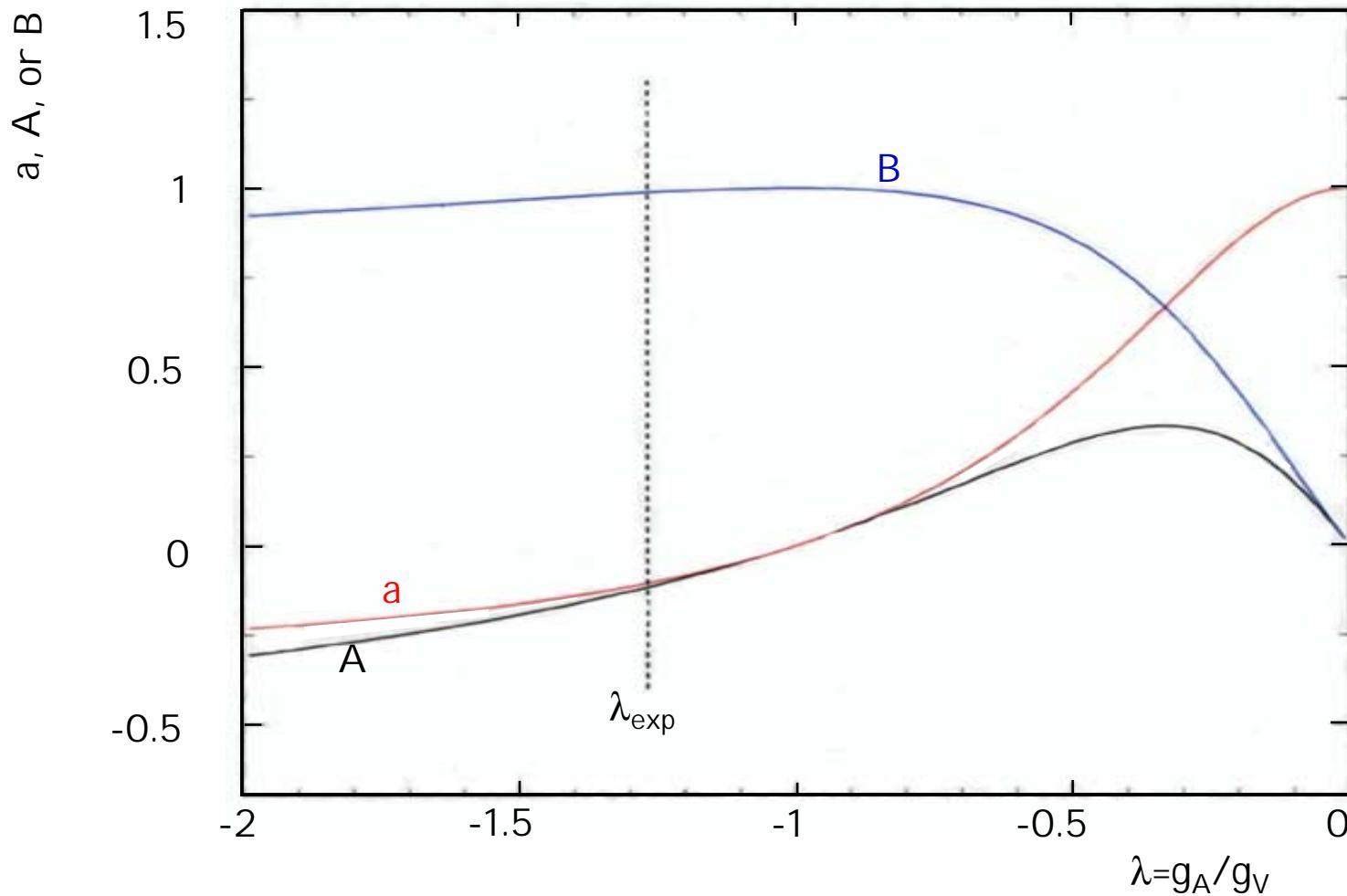
Weak charged coupling constants:

According to CVC, $G_V = V_{ud} g_V G_F, \quad g_V = 1$

$$G_A = V_{ud} g_A G_F, \quad g_A \approx 1.26 \quad \} \text{test CKM matrix unitarity}$$

G_F is universal coupling constant in weak interaction
Known from μ and τ decays

Neutron β -decay correlation sensitivity to λ



Universality of Weak Interaction

- Weak quark eigenstates are different from quark mass eigenstates

$$\begin{pmatrix} \mathbf{d}_w \\ \mathbf{s}_w \\ \mathbf{b}_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} \mathbf{d} \\ \mathbf{s} \\ \mathbf{b} \end{pmatrix}$$

$$\begin{pmatrix} \mathbf{d}_w \\ \mathbf{s}_w \\ \mathbf{b}_w \end{pmatrix} = \begin{pmatrix} 0.975 & 0.22 & 0.005 \\ 0.22 & 0.97 & 0.04 \\ 0.005 & 0.04 & 0.99 \end{pmatrix} \begin{pmatrix} \mathbf{d} \\ \mathbf{s} \\ \mathbf{b} \end{pmatrix}$$

- Universality implies CKM matrix unitarity

$$V^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 \stackrel{?}{=} 1$$

- Diagonal elements dominate

Unitarity of CKM matrix tests existence of further
quark generations and possible new physics

Biggest uncertainty is from λ :

Measuring V_{ud} with Neutron Decay

$$V_{ud}^2 = \frac{K/\ln 2}{G_F^2 (1 + \Delta_R^V) (1 + 3\lambda^2) f(1 + \delta_R) \tau_n}, \quad \lambda = G'_A/G'_V \approx -1.265$$

$$\begin{aligned} 1 - V^2 &= 0.0047 \pm 0.0051 \\ &= 0.0047 \pm \frac{0.0049}{\lambda} \pm 0.0010 \pm 0.0010 \pm 0.0007 \\ &\qquad\qquad\qquad \tau_n \qquad\qquad\qquad V_{us} \qquad\qquad\qquad RC \end{aligned}$$

$$\frac{d\lambda}{da} = 3.3$$

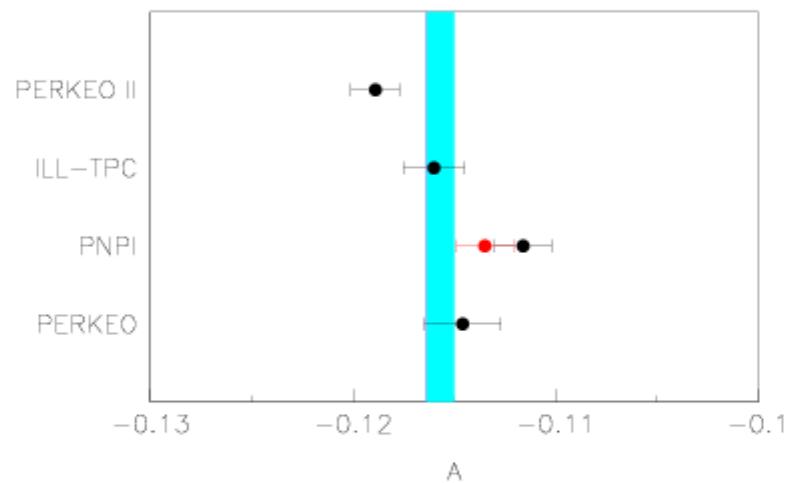
$$\frac{d\lambda}{dA} = 2.6$$

$$\frac{d\lambda}{dB} = 13.4$$

$$\Delta a = 2.3 \times 10^{-4} \quad \Delta A = 3.0 \times 10^{-4} \quad \Delta B = 0.6 \times 10^{-4}$$

$$\rightarrow \Delta V_\lambda^2 = 0.0010$$

Existing Measurements of A



$$A = -0.1157 \pm 0.0007 \text{ (0.0015)} \quad \chi^2 = 16.2 \quad P = 0.001$$

$$A = -0.1162 \pm 0.0007 \text{ (0.0012)} \quad \chi^2 = 9.5 \quad P = 0.023$$

Sources of Systematic Error in Previous Experiments

- • Neutron polarization determined in auxiliary experiments
- • Poor detector properties
 - Resolution, efficiency, stability, homogeneity
- • Singles measurements: background subtraction needed
 - Fiducial volume defined by material apertures
 - Energy loss, scattering
 - Magnetic field pinch reverses particle trajectories
- • Electron back-scattering from detectors

Collaboration :

Neutron β -Decay Measurements with a Pulsed Cold Neutron Beam

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Introduction

- Neutron β -decay provides severe test of the Standard Model
- Intense pulsed cold neutron beams will be available
- New technologies control systematics
Silicon detectors, ^3He polarizers, pulsed beams

Goals

-Determine $\lambda = G_A/G_V$ redundantly

Measure both a and A (first precision measurement of "a")

Determine A from e^- and p asymmetries

Reduce technical risk for CKM unitarity test

-Search for Fierz interference term b

Sensitive to scalar and tensor couplings

Non-zero value suggested by π^+ β -decay results

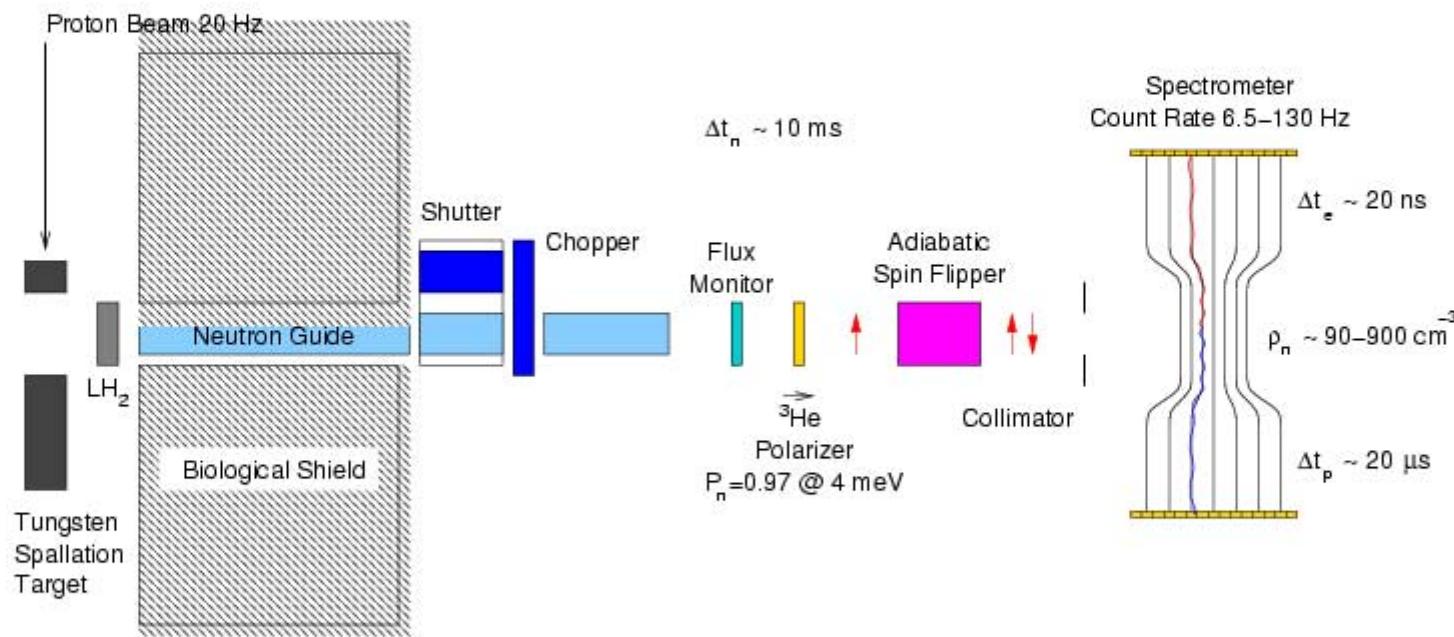
Never measured

-Measure B precisely

Sensitive to deviations from V-A theory

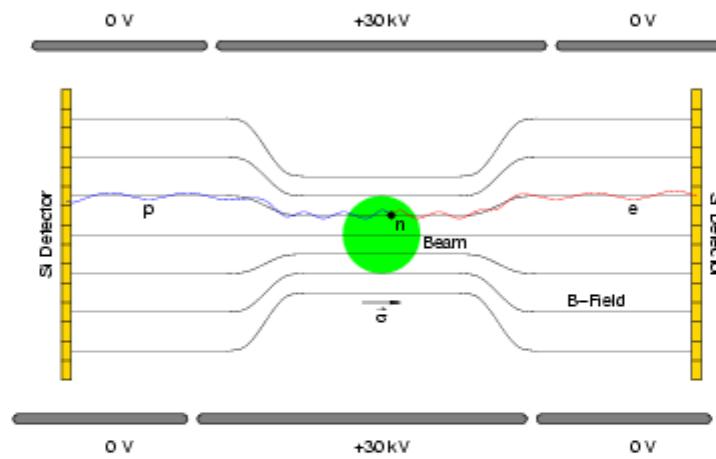
Pulsed

Neutron β -Decay with Cold Neutron Beams



LANSCE Configuration

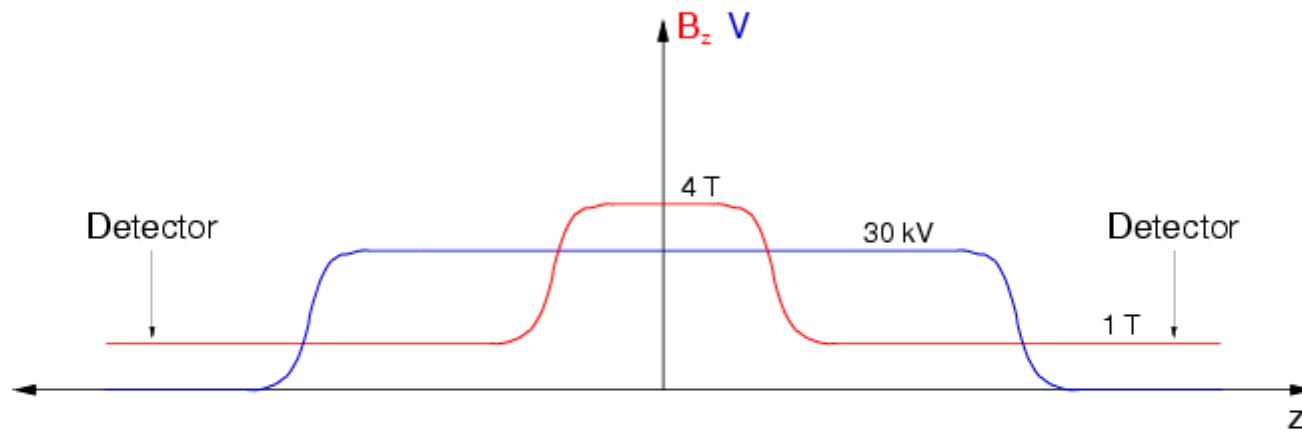
Neutron β -Decay Spectrometer



- Two 2π detectors
- e backscattering monitored (a, B)
- $\Delta t \sim 1$ ns
- $\Delta E \leq 5$ keV
- Dead layer has to be very thin
- $e - p$ coincidence
- Beam imaged by detectors
- *In situ* background measurement
- No material apertures

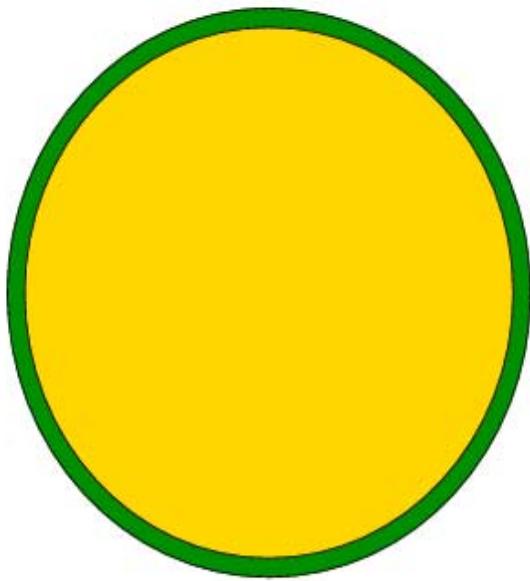
Magnetic and Electric Fields

(for symmetric geometry)

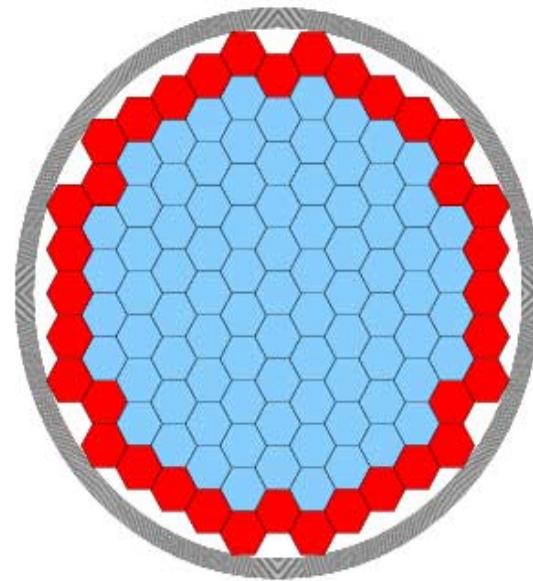


- Magnetic field expansion: \vec{p}_e more normal to detector
- Magnetic field gradient reflects backscattered electrons
- Electric field accelerates protons

Preliminary Detector Design



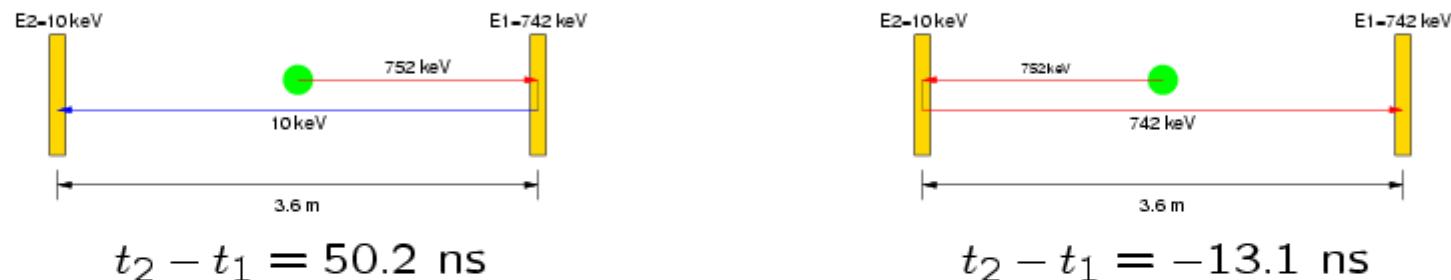
Junction Side
(Particles Incident)



Ohmic Side
(Readout)

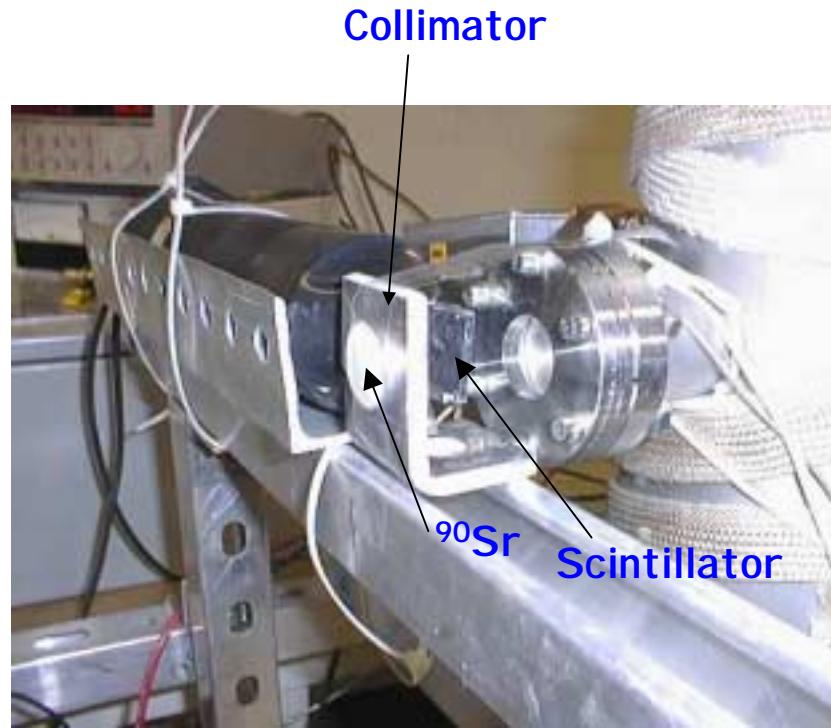
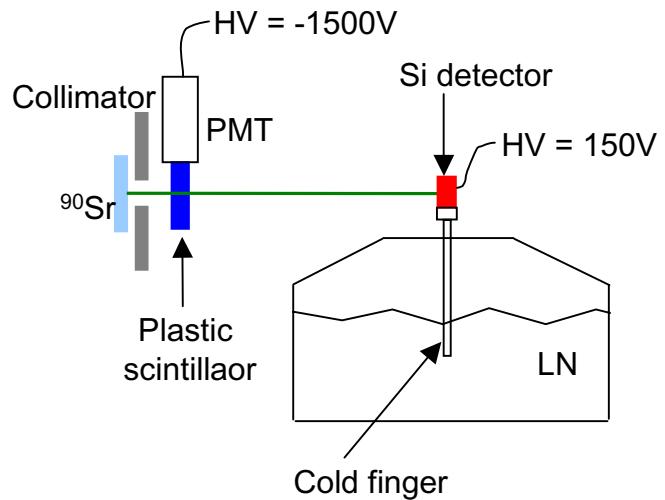
15 cm Diameter, 2 mm Thick, 127 Channel
(with a thin Au dead-layer)

Detector Timing Resolution

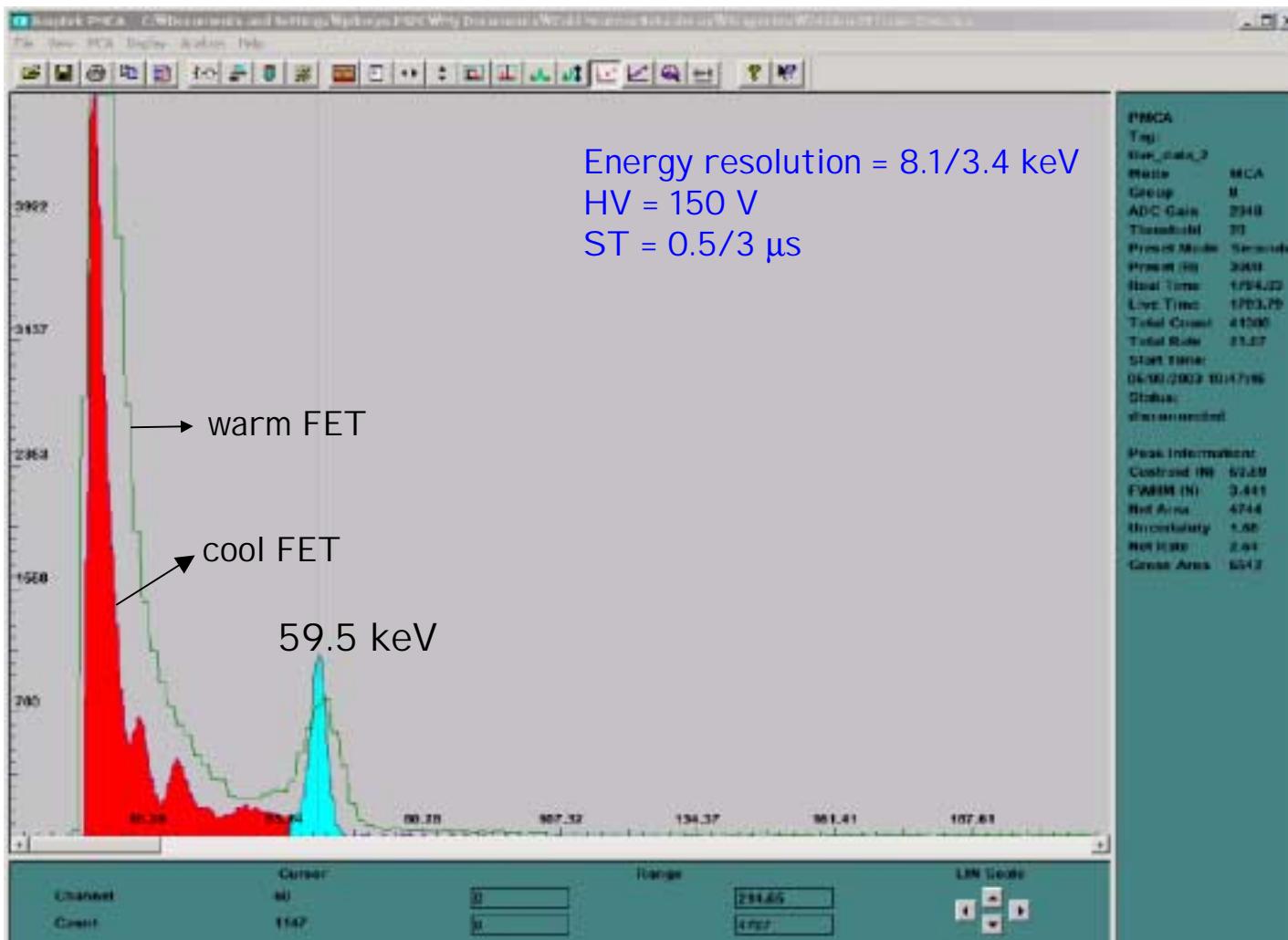


- Timing information needed for e- backscattering events for B
- Worst-case events have low-E electron in one detector
- Must achieve timing resolution $\sim 1 \text{ ns}$ for 200-keV electron

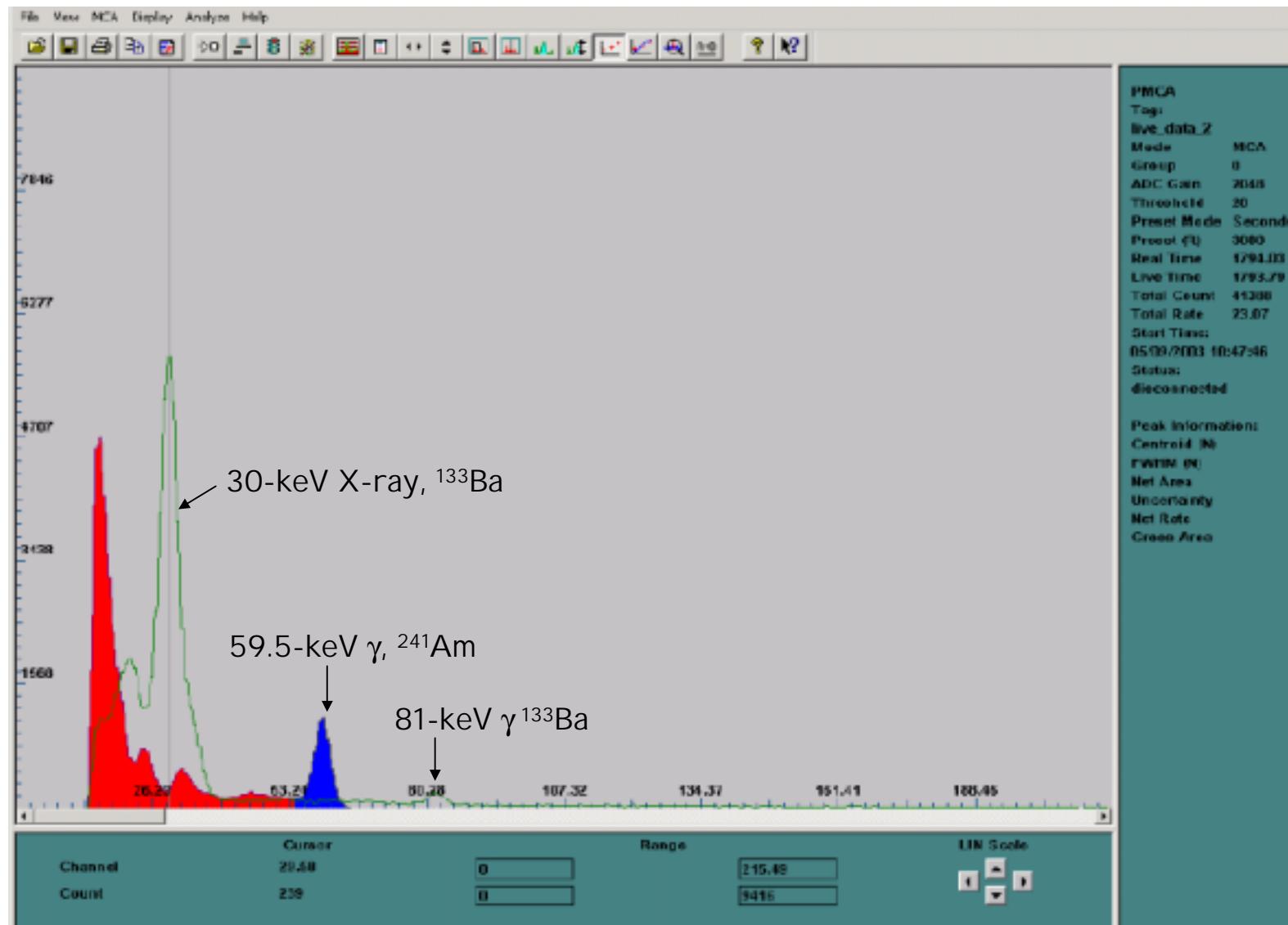
Silicon Detector Timing Measurement Setup (coincidence with scintillator pulse)



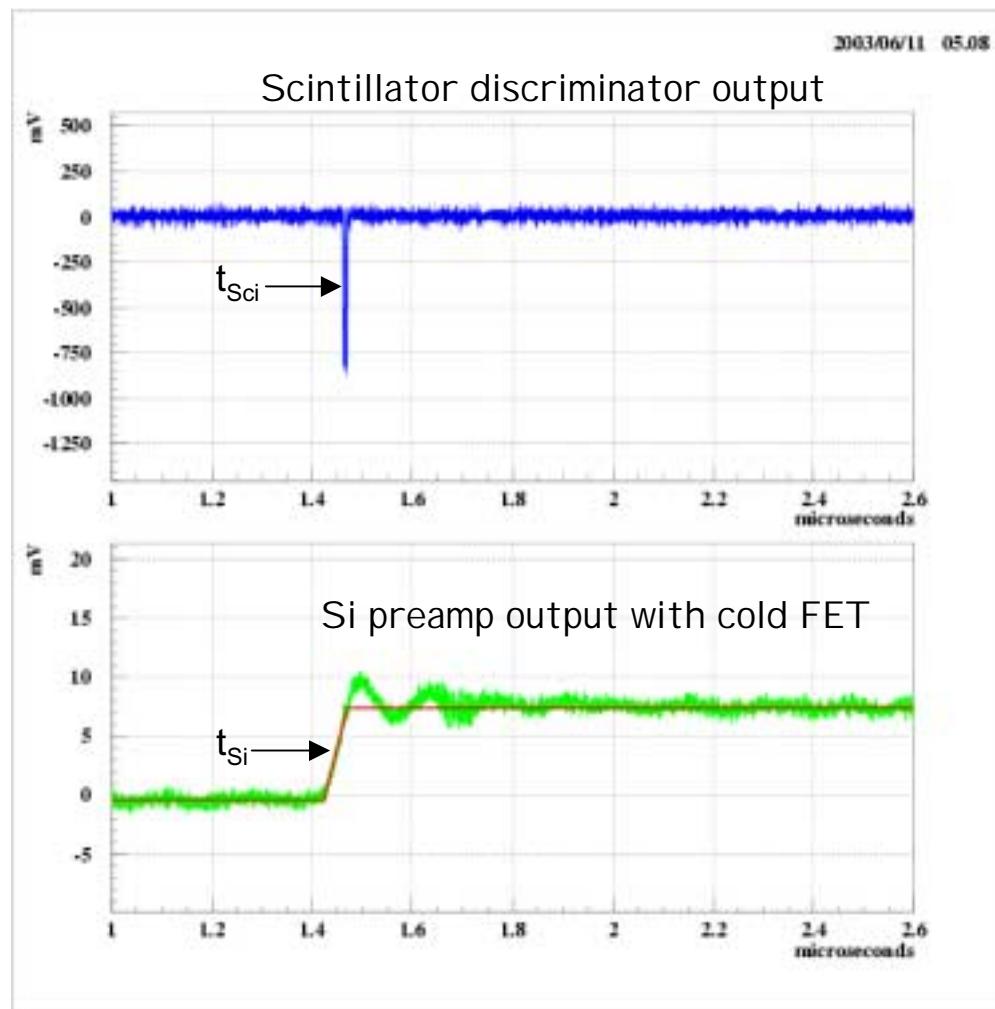
Pulse-height spectra of ^{241}Am - warm/cool FET



Pulse-height spectra of ^{241}Am and ^{133}Ba

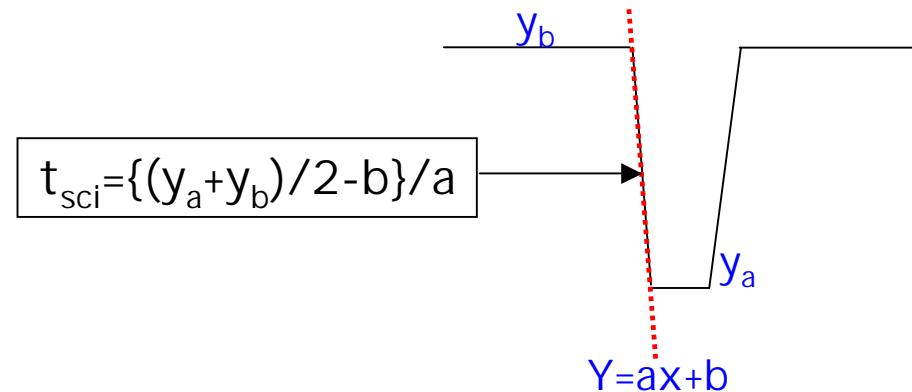


Waveforms of Scintillator and Silicon detector

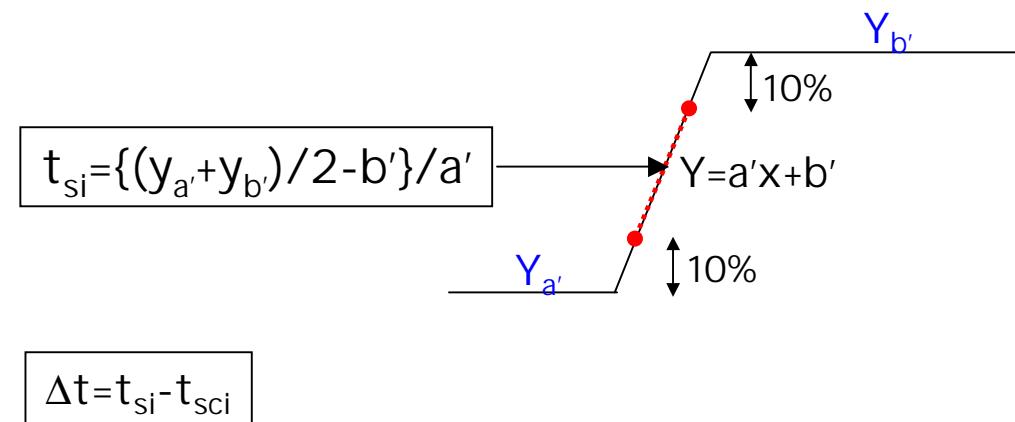


Waveforms Fit Analysis

Scintillator signal:



Si detector preamp signal:



Theoretical calculation for a warm FET

$$\Gamma = 2.35 \times \frac{V_n C \delta E}{E} \sqrt{\frac{T_{rise}}{2}} \times 2$$

V_n : FET noise, 10^{-9} (V/ $\sqrt{\text{Hz}}$)

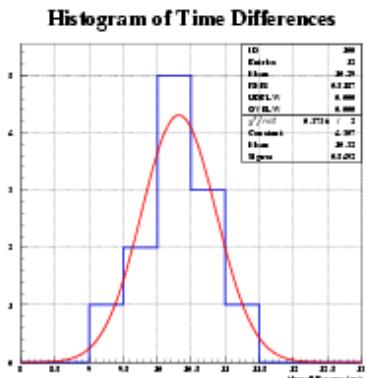
C : capacitance

δE : energy/electron - hole pair for Si

E : electron energ

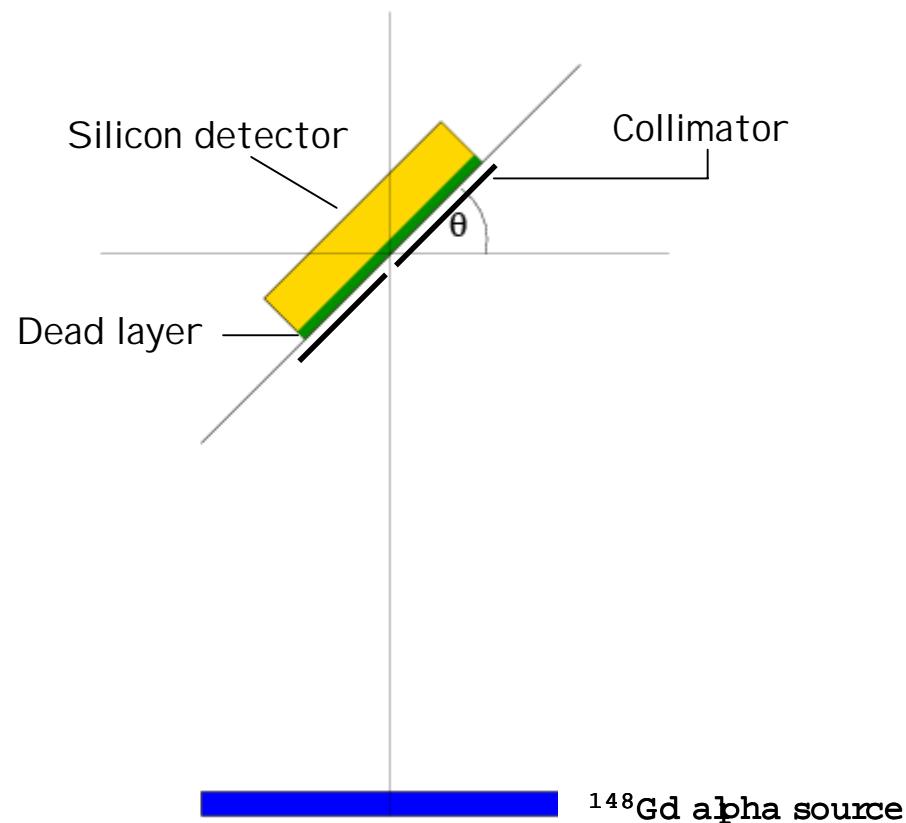
$$\Gamma = 1.02 \text{ ns}$$

Silicon Detector Timing Results

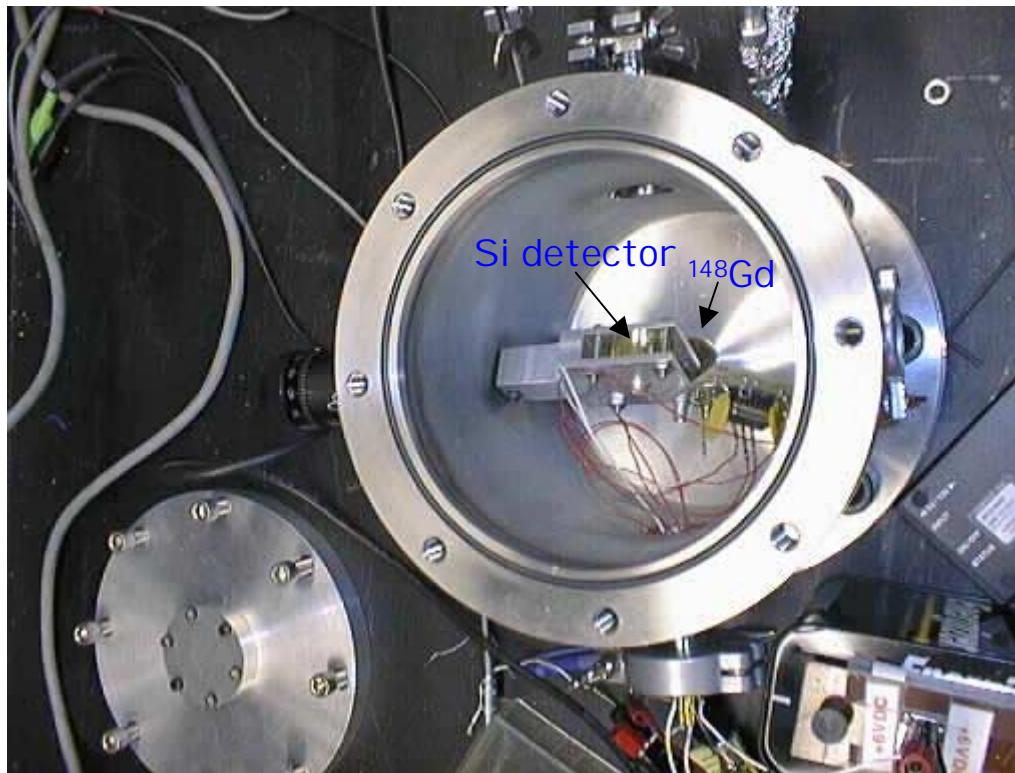


- Preliminary $\Delta t = 1.39 \pm 0.40$ ns for 170 keV (1.02 ns theoretical limit)
- Figure-of-merit 236 ± 68 keV·ns
- Sufficient for proposed spectrometer
- Expect $\times 3.3$ improvement (cooled FET, increased detector bias) ← working on

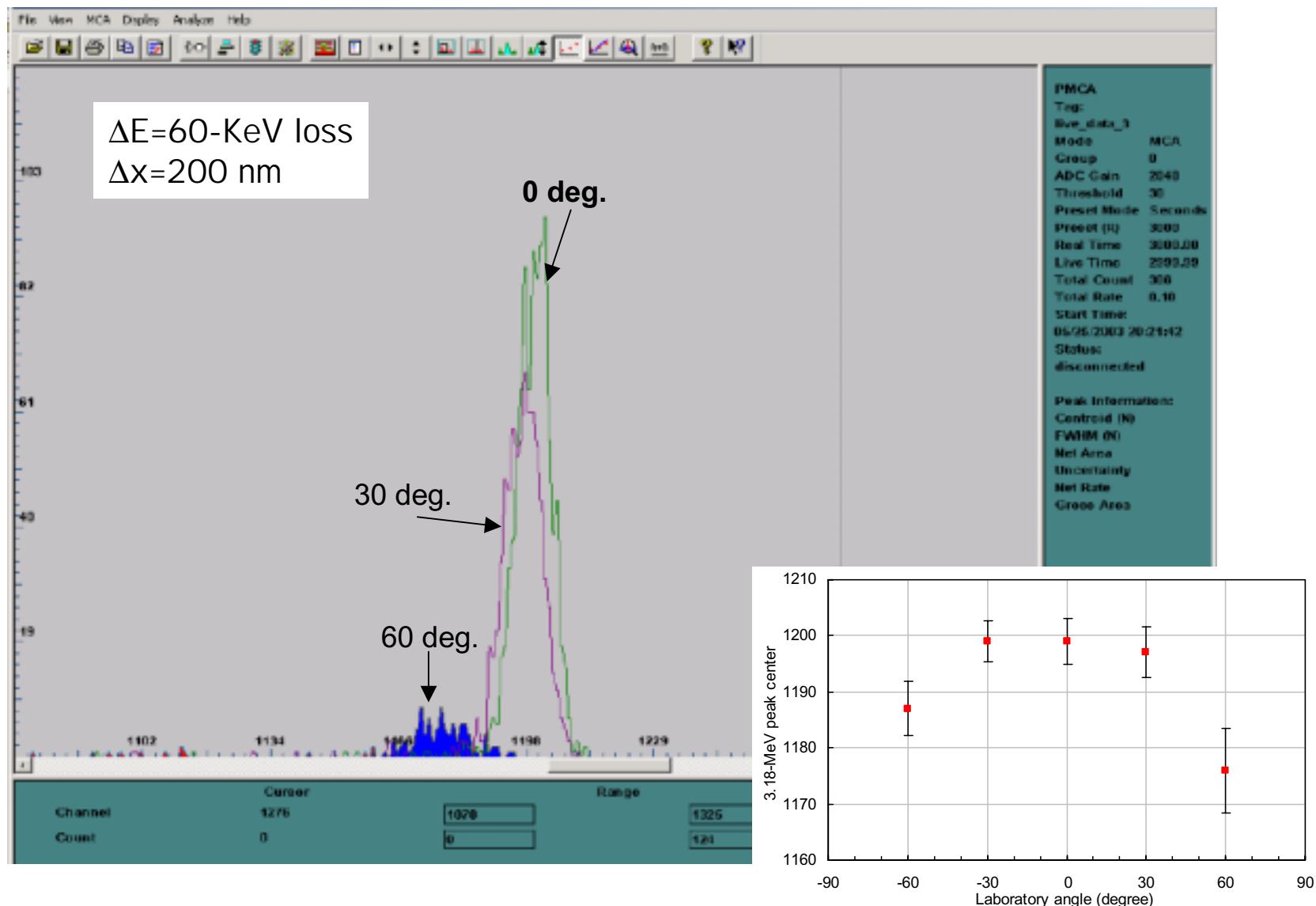
Dead Layer Measurements



Dead-layer Measurement Apparatus



Test 300 μm -thick Si detector to measure dead-layer measurement with 3.2-MeV alpha



Summary

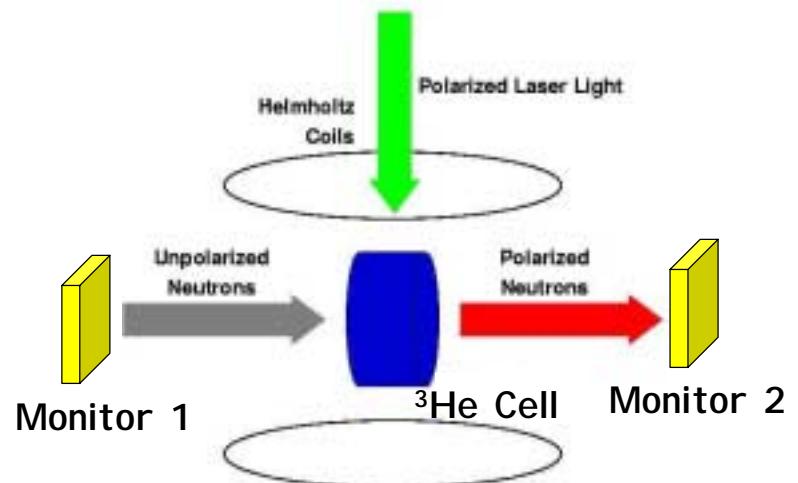
- Important test for SM of weak interaction
- Use Pulsed Cold Neutron β -decay
- Measure a , b , A , and B with 0.1% precision
- First precision measurements from Pulsed Cold Neutron decay using coincidence timing technique
- To reduce systematic and statistical uncertainty, it is very important to have redundant λ , polarization of neutron, large size with thin-dead layer Si detector, and timing coincidence technique
- Demonstrated criteria of a spectrometer to observe proton and backscattered electron with a small size of Si detector
 $\Delta E = 3.4 \text{ keV}$ for 60-keV gamma (with cool FET)
 $\Delta t = 1.4 \text{ ns}$ (with warm FET)
Energy loss in a dead layer of Si detector
- Schedule first experiment at LANSCE and then SNS

Neutron Polarizer

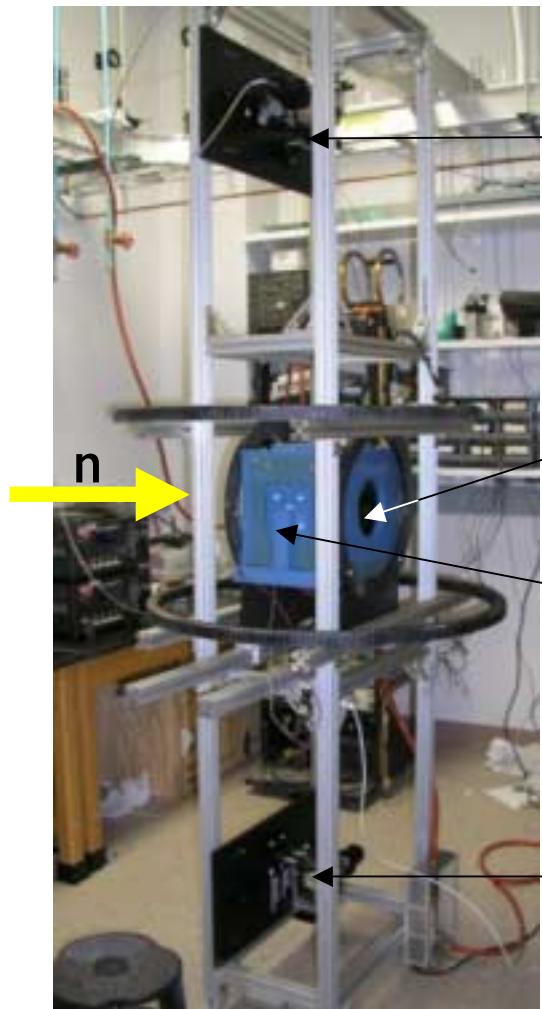
Polarized ^3He Neutron Spin Filter

- Single cell Optical Pumping
Spin Exchange w/ Rb
- $P_n = \tanh(nl\sigma P_3)$
- $t_n = t_o \exp(-nl\sigma) \cosh(nl\sigma P_3)$

, where P_n : neutron polarity,
 n : atom density of ^3He ,
 l : the thickness of the cell,
 σ : ^3He absorption cross section,
 P_3 : ^3He polarization
 t_n : # of polarized neutron
 t_o : # of unpolarized neutron



^3He Spin Filter



Optics

^3He cell



Oven

Optics

- Sealed single cells made at NIST
- Largest size in the world
- 11 cm diameter
- 4-5 atm-cm thick
- Long T_1 's \Rightarrow high P_3
- 4 cells available

Running at UM since Jan. 2003